NASA TT F-11,844

NEW TECHNIQUES IN INVESTIGATING HANDLING QUALITIES

H. Frohlich, W. Kreil, G. Schweizer,
K. Stopfkuchen

From: Aerospace Proceedings 1966, Royal Aeronautical Society, Centenary Congress and International Council of the Aeronautical Sciences, 5th Congress, London, September 12-16, 1966, Volume 2, pages 931-962.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON JULY 1968

NASA TT-F-11,844

NEW TECHNIQUES IN INVESTIGATING HANDLING QUALITIES /931

H. Frohlich, W. Kreil, G. Schweizer,
K. Stopfkuchen

The design of the controls of a manned aircraft in the development stage requires knowledge of the dynamic bahavior of the pilot-aircraft system with the utmost accuracy possible. While with presently available means it is in general easy to simulate the behavior of an aircraft in a model, the representation by models of the dynamic behavior of man is fraught with considerable difficulties.

The model of a pilot generally used heretofore does not always lead to satisfactory results. A new model is thus proposed for discussion; it differs from the conventional concept by the fact that its parameters are not assumed to be constant, but that they are stochastically variable. It is assumed that the stochastic variations of the parameters are stationary. The model proposed can be used both in simulation and in free flight for measurement purposes. Control experiments were performed with the aid of the pilot model both on a VTOL transport and various helicopters. Results are presented for simulated and for free flights. The measurements indicate both the state of proficiency and the temperament of different pilots and the degree of training of the same pilot. Changes in control means and instruments with the same aircraft and pilot are recognized in the performance spectra. Some of the measured results are compared with pilot judgments.

1. Introduction

Experience shows that the dynamic behavior of a man-machine system is satisfactory only if the characteristics of the system are adapted to the capabilities of man. This fact has been known for a long period of time. As a result, /933 attempts have been made for at least twenty years to describe the dynamic behavior of man in order to be able to optimally design systems in which there is interference by human beings /1/.

The first models describing the dynamic behavior of man as a controller were presented in 1944 by Tustin /2/. The models, which describe transfer charactersitcs from sensation to the mechanical motion, are all composed in essence of a linear part and an additive source of noise. The noise signal has broad-band characteristics and is taken as not correlated with sensory information.

$$F_p(j\omega) = \frac{K e^{-j\omega T_T}}{1 + j\omega T_N} \cdot \frac{1 + j\omega T_L}{1 + j\omega T_I} \qquad (1)$$

A diagram of such a model is presented in Fig. 1.

Although a large number of investigations have been performed in the meantime with the purpose of improving and adding to the model, the latter has changed very little. This and the fact that analytical models of man in the form illustrated in Fig. 1 as controller are not usually applied to the design of systems indicate that numerous problems remain unsolved and that further studies are necessary.

Since to date analytical methods have not been overly successful in the characterization of man-machine systems, subjective descriptive methods are frequently used. Among others, numerous experiments involving different experimental persons have shown that second-order systems can be controlled by a human controller in a satisfactory manner if the damping capacity and the natural resonance frequency of the system are in a definite relationship to each other. The experiments were conducted primarily with respect to the longitudinal motion of an aircraft (Fig. 2).

Due to the qualitative nature of pilot statements, the method of conducting numerous experiments with individual experimental persons and entering their subjective statements into families of characteristics does not provide satisfactory data for the design of controls. The optimum dimensioning of control instrumentation for an aircraft developed in accordance with the contemporary stand of technology requires a much more accurate quantitative knowledge of pilot behavior. Such data can be obtained only by an analysis of the transfer behavior of man. In the course of research conducted in the House of Dornier controllability investigations are being performed to determine the extent to which the subjective judgment of the pilot can be supported and supplemented by measurements of pilot behavior. The results and the theoretical foundations of these investigations are presented.

2. Dynamic Models of the Behavior of Man as Controller /934

The transfer behavior of man depends on a multitude of different effects. At a first glance it would therefore appear that it is nearly impossible to find an adequate model of the dynamic behavior of man having validity over a wide range of /935 application.

Experience gained to date from numerous experiments showed, however, that the structure of a model describing the dynamic behavior of man while controlling stationary processes does not vary fundamentally as the result of the various physiological and physical influences, only its parameters are changing.

The investigation of the House of Dornier show that the dynamic behavior of man while controlling stationary processes can be represented by a linear model with stochastically variable coefficients.

3. Characteristics and Proof of Validity of the Dynamic Models Chosen

Fig. 1 and 3 represent two different man-machine systems, characterized by two different models of the dynamic behavior of man. In both models $\sigma(t)$ represents an unknown interference signal which is always present; for the purpose of measuring it may be introduced artifically. The model shown in Fig. 1 is generally found in the literature. It had been described in the introduction. If this model is made the basis of measurements, the dynamic behavior of man cannot be measured when the control signal $i(t)$ or the known interference signal $z(t)$ is missing. The following derivation illustrates the condition.

Let generally $\phi(t)$ be the signal for sensory perception, $K(t)$ the mechanical operation of an operating control. In standard flying experiments the artificial interference signal $z(t)$ is missing. The interference signal $\sigma(t)$, which is always present, and the additionally introduced additive noise signal $p(t)$ of man are both unknown. The following relationship exists between the cross output spectrum $S_{\phi k}(j\omega)$ and the auto-output spectrum $S_{\phi\phi}(\omega)$

$$\frac{S_{\phi K}(j\omega)}{S_{\phi\phi}(\omega)} = -\frac{1}{F_s}\left[1-\frac{1+F_sF_p}{1+[S_{pp}(\omega)/S_{\sigma\sigma}(\omega)]}\right] \qquad (2)$$

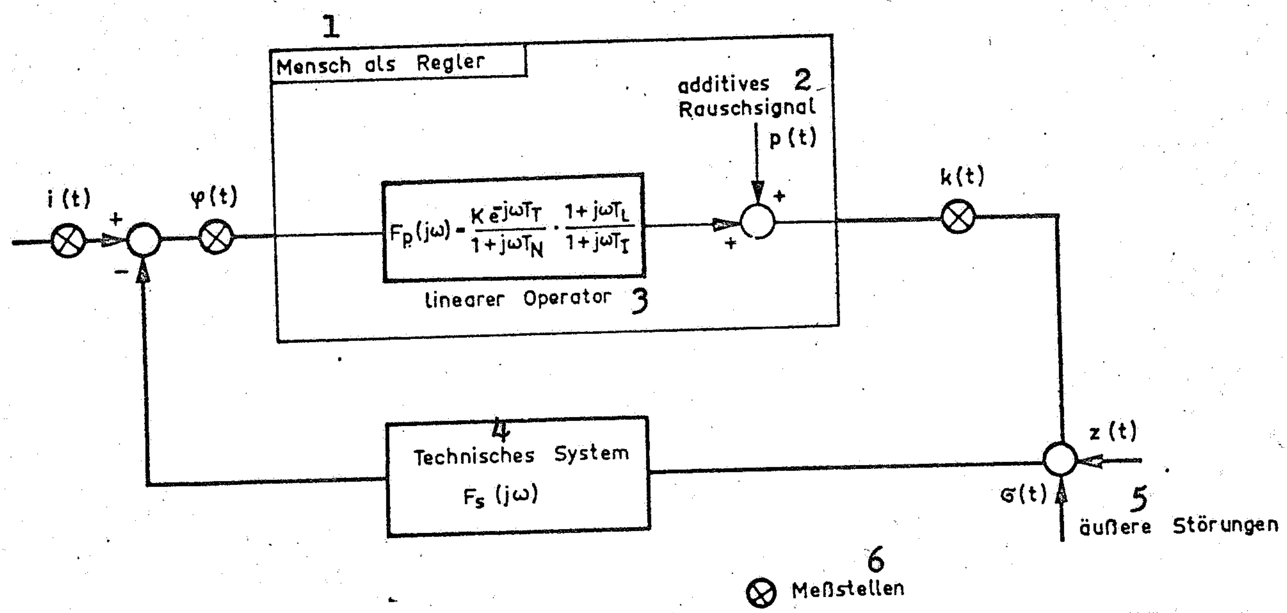


FIGURE 1. Man as Member of a Sequential Control System (Additive Model of Man)

KEY: 1. Man as controller, 2. Additive noise signal, 3. Linear operator, 4. Technical system, 5. External interference, 6. Measuring locations

If the interference signal $\sigma(t)$ is large compared to the noise signal $p(t)$ of the pilot, Equation 2 gives the frequency response of the pilot.

$$\frac{S_{\phi K}(j\omega)}{S_{\phi\phi}(\omega)} = F_p(j\omega) \quad \text{for} \quad \sigma(t) \gg p(t) \qquad (3a)$$

Measurements show, however, that this is generally not true. In most cases $\sigma(t)$ is small in comparison with $p(t)$. Then, if the model of Fig. 1 is used, instead of the transfer function of man the negative inverse frequency response of the loop is obtained: /937

$$\frac{S_{\phi K}(j\omega)}{S_{\phi\phi}(\omega)} = -\frac{1}{F_s(j\omega)} \quad \text{for} \quad \sigma(t) \ll p(t) \qquad (3b)$$

The transfer function of man thus be obtained only with a known additional interference signal $z(t)$ or in the case of sequential control with the aid of the control signal $i(t)$. The following relationship can then be formulated:

$$\frac{S_{z\phi}(j\omega)}{S_{zz}(\omega)} = \frac{F_s(j\omega)}{1+F_s(j\omega).F_p(j\omega)} \qquad (4)$$

$$\frac{S_{zk}(j\omega)}{S_{zz}(\omega)} = \frac{F_s(j\omega).F_p(j\omega)}{1+F_s(j\omega).F_p(j\omega)} \qquad (5)$$

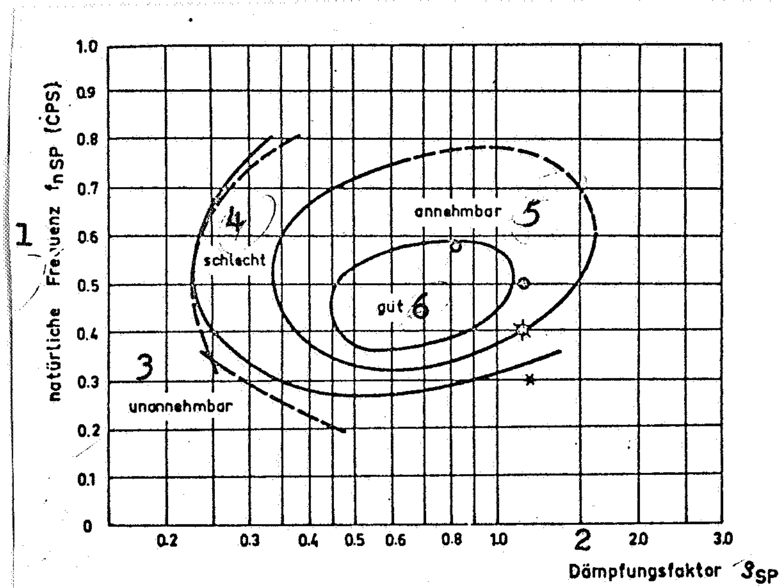
It is assumed here that the signals $z(t)$ and $p(t)$ are not correlated with each other.

Division of the two results yields the desired transfer function for the dynamic behavior of man.

$$F_p(j\omega) = \frac{S_{zk}(j\omega)}{S_{z\phi}(j\omega)} \qquad (6)$$

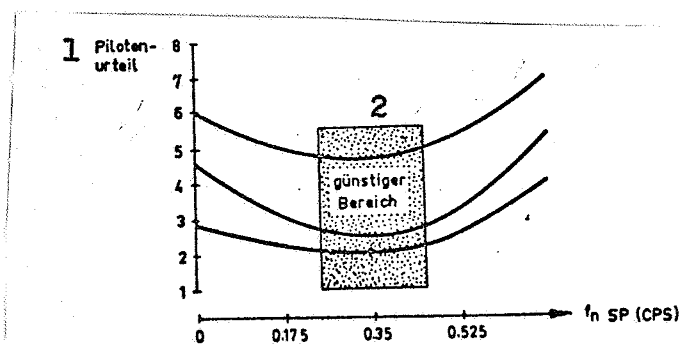
The result of Equation (6) is in formal agreement with the desired result. I practice, however, such measurements cannot be performed, for the following reasons: experience shows that the behavior of man varies with the task facing him. In the case of gross interference the pilot behaves differently than with small disturbances. If one desires to

The Dependence of Resonance Frequency and Damping in the Controllability of Incident Angle Vibration /934



Keys: 1. Natural frequency, 2. Damping factor, 3. Unacceptable, 4. Poor, 5. Acceptable, 6. Good

The Relationship of Pilot Judgment and Resonance Frequency in Angle Position-Controlled Hovering Flight



Keys: 1. Pilot judgment, 2. Favorable range

FIGURE 2. Relationship Between Pilot Judgment and the Parameters of a Second-Order System

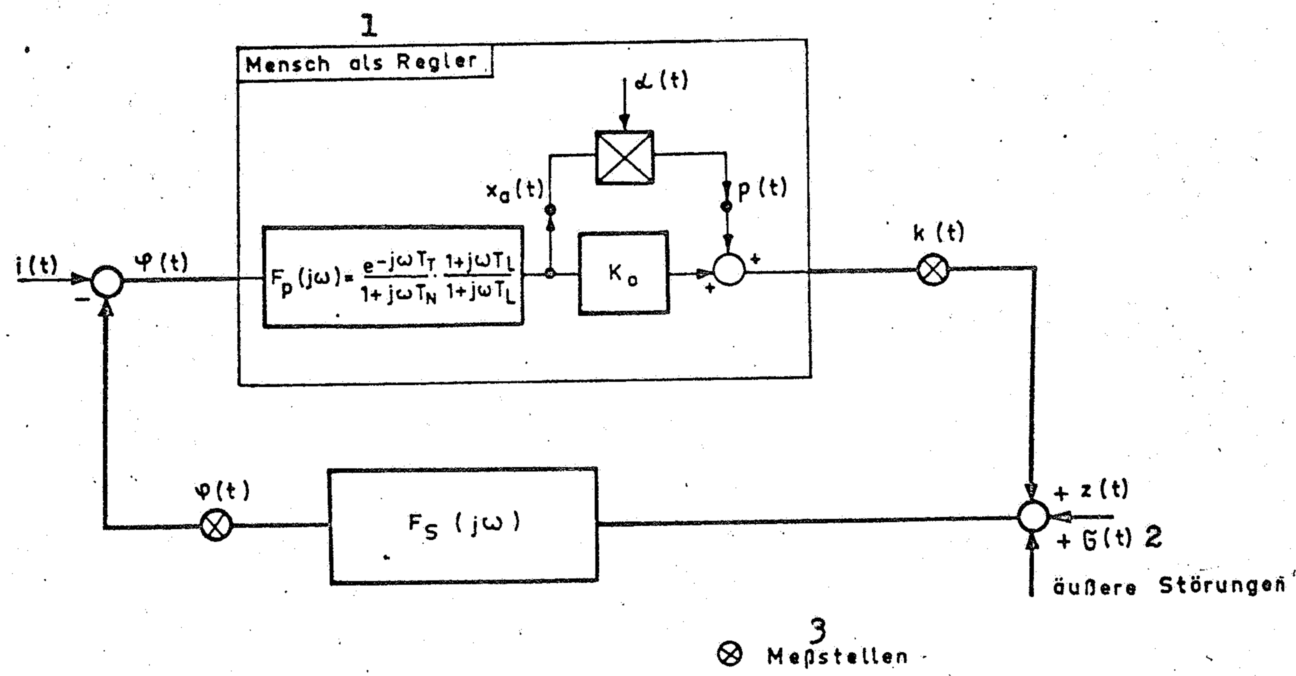


FIGURE 3. Man-Machine System with Multiplicative Noise

Keys: 1. Man as controller, 2. External interference, 3. Measuring locations

/936

determine the behavior of the pilot during an only slightly disturbed flight, the $x(t)$ signal cannot be overly large. This makes pilot noise generally the dominant source of noise. In the case of a small $x(t)$ interference signal it is hardly possible to measure accurately in accordance with Equations (4) and (5). If, on the other hand, $x(t)$ is chosen sufficiently large and care is taken that the signal has an adequate volume in the frequency range of interest, the result is -- except for some individual cases, the simulation of a strongly disturbed flight. If, therefore, the model of Fig. 1 would be valid, it would be impossible to measure the frequency response of the pilot during a nearly undisturbed flight.

The model of the dynamic behavior of man presented in Fig. 3 assumes stochastically variable coefficients. The essential characteristics, as derived /3, 4/, of the model are the statistic independence of the stochastic $\alpha(t)$ signals with the initial signal $k(t)$ which represents the mechanical activation of control devices. One thus obtains

$$\begin{aligned} E\{\alpha(t) \,.\, x_a(t+\tau)\} &= 0 \\ E\{\alpha(t) \,.\, k(t+\tau)\} &= 0 \end{aligned} \tag{7}$$

and therefore /939

$$S_{\phi k}(j\omega) = F_p(j\omega) \,.\, S_{\phi\phi}(\omega) \tag{8}$$

It is seen from Equation (8) that assuming that the model of Fig. 3 is correct, the transfer function of the constant part of the dynamic behavior of man is readily measurable. The two necessary conditions: an existing small interference signal $\sigma(t)$ and an adequate output of the signals $\phi(t)$ and $k(t)$ have so far always been satisfied in problems of interest.

With the aid of Equation (8) and the derivations cited /3,4/ the spectrum of man noise can be measured. One obtains

$$S_{pp}(\omega) = S_{kk}(\omega) - |F_P(j\omega)|^2 \,.\, S_{\phi\phi}(\omega) \tag{9}$$

Anticipating during the measurement an external interference signal $x(t)$ of sufficient output makes it possible to determine the transfer function of man in accordance with

Equation (4) to (6) in the manner decribed above, in the case of a model with stochastic coefficients also. A number of experiments in which an interference signal $z(t)$ was artificially introduced during the flight, was therefore performed. Assuming that Fig. 3 is correct, measurements according to Equations (4) to (6) and the evaluation of measurements in accordance with Equation (8) should yield identical results. Results are presented in Fig. 4. It is seen that the time-variable model conforms to actual conditions.

Experiments with nearly negligible interferences during flights yield similar results, as shown in the following. If the model of Fig. 1 is correct, in measurements in which the pilot noise is dominant, one should obtain the inverse frequency response of the loop, as indicated by Equation (3). Experiments performed with a hover craft (Fig. 5) revealed that this does not occur.

The frequency response of the angle position-controlled hover craft was measured first with the aid of an experiment in which the craft was supported on a telescoping column.

Subsequently, the frequency response was again measured during various free-flight experiments. Measurements with the aid of the cross performance spectrum with the model of Fig. 1 yields

$$\frac{S_{k\phi}(j\omega)}{S_{kk}(\omega)} = F_s(j\omega)\left[\frac{1-(1/F_pF_s)[S_{\sigma\sigma}(\omega)/S_{pp}(\omega)]}{1+|F_sF_p|^2[S_{\sigma\sigma}(\omega)/S_{pp}(\omega)]}\right] \tag{10}$$

According to Equation (10), the transfer function of the loop is obtained when $\sigma(t) \ll p(t)$. During flights under normal conditions the transfer function $F_s(j\omega)$ was obtained in the measurements as shown in Fig. 6. Thus the condition of $\sigma(t) \ll p(t)$ was satisfied. In calculations with the cross output spectrum $S_{\phi K}(j\omega)$ in accordance with Equation (8), the constant part of the pilot transfer function -- as seen in Fig. 7 -- and not the inverse transfer function of the loop was achieved, which should have been obtained in accordance with Fig. 1. Therefore it must be true that the model with stochastic coefficients of Fig. 3 is in better agreement with actual conditions during quiet flights, i.e. in simple problems, than the model with the additive noise source which heretofore has always been used. /940

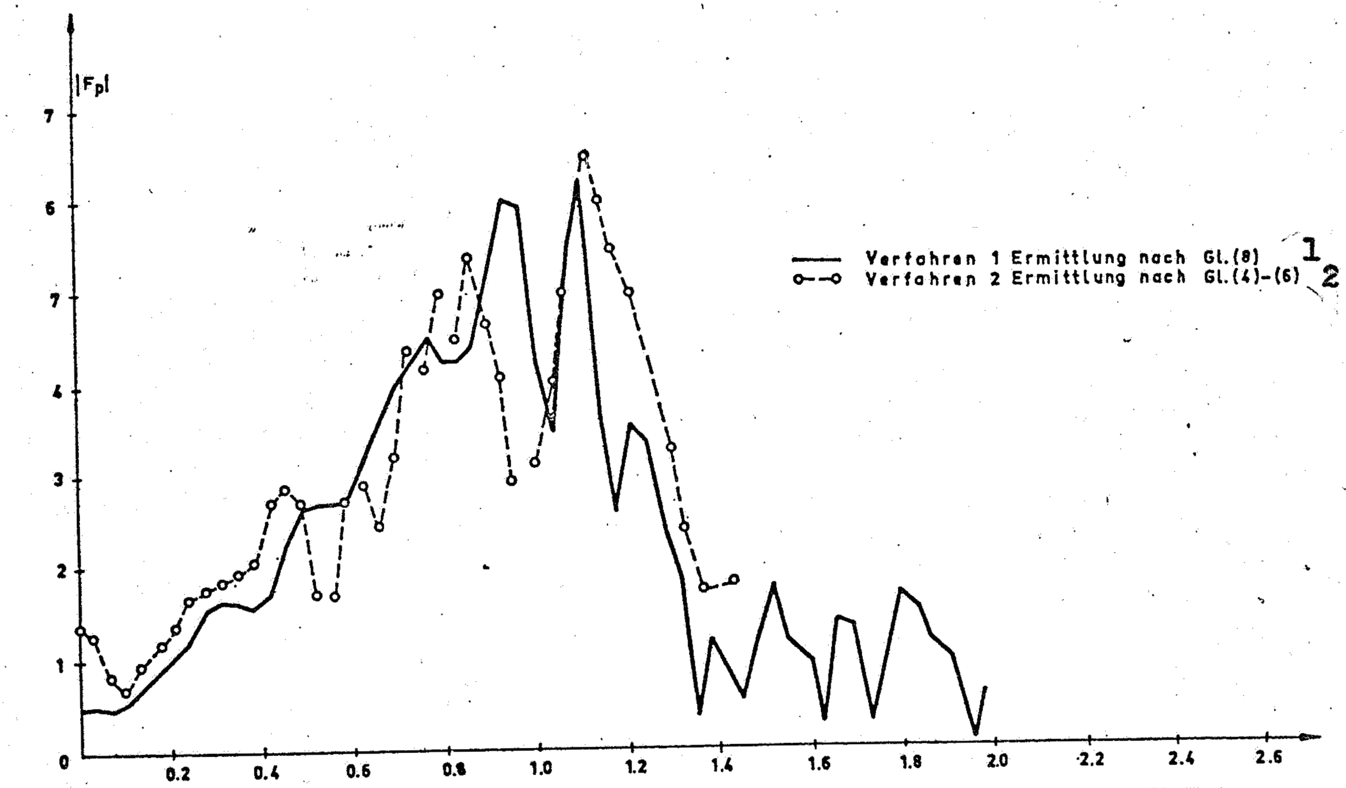


FIGURE 4. Magnitude of Pilot Frequency Response in the Roll Control of the Hover Craft

Keys: 1. Method 1: Determination according to Equation (8).
2. Method 2: Determination according to Equation (4) to (6).

Compared with the model of Fig. 1, the model of Fig. has obviously entirely different dynamic characteristics. The dynamic behavior of the first in a man-machine loop is completely characterized by the transfer function $F_p(j\omega)$. The dynamic behavior of the time-variable model on the other hand is determined by both the stochastic amplification and the transfer functions of the constant part $F_p(j\omega)$. Measurements of the transfer function $F_p(j\omega)$ by itself thus result in an incomplete description.

Experiments show to date that although the behavior of man varies in time, it frequently appears to be linear during an experiment involving the same problem. To prove this assumption, the following argument is presented: if behavior with stochastically varying amplification is linear, the following expectation value can be formulated (Fig. 8a):

$$E\{\phi(t)\,.\,K_0\,.\,x_a(t+\tau)\} = K_0\Phi_{\phi x_a}(\tau) \qquad (11)$$

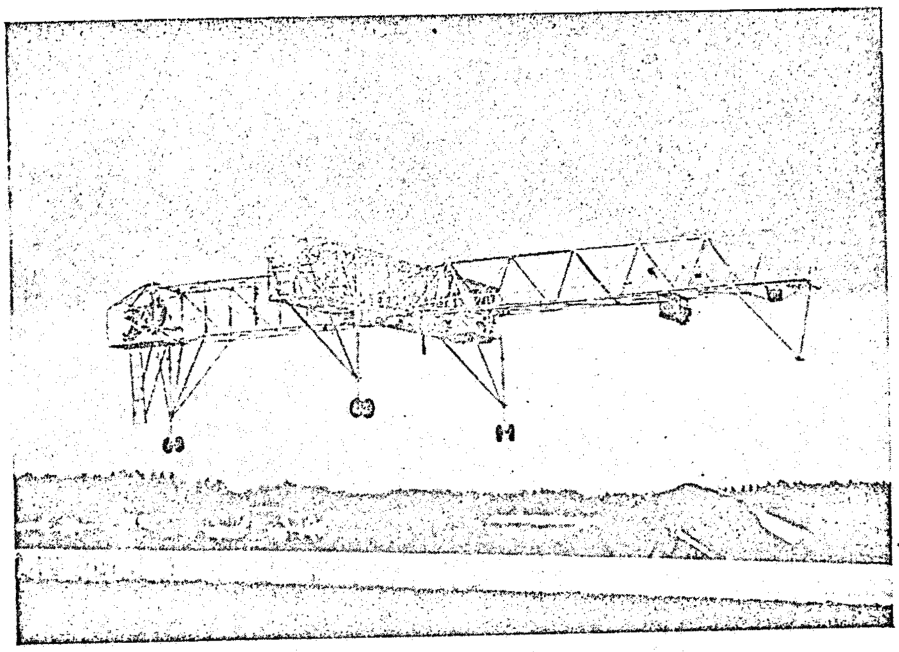


FIGURE 5. Free-Flying Hover Craft

In the same manner, the expectation value

$$E\{\phi^3(t) . K_0 . x_a(t+\tau)\} = 3K_0\Phi_{\phi x_a}(\tau) . \Phi_{\phi\phi}(0) \tag{12}$$

can also be calculated. If the degree of amplification, as shown in Fig. 8b, changes e.g. with the third power and simultaneously varies stochastically, the following expectation value obtains:

$$\begin{aligned} &E . \{\phi^3(t) . [K_0 . x_a(t+\tau) + K_1 x_a^3(t+\tau)]\} \\ &= 3K_0\Phi_{\phi x_a}(\tau) . \Phi_{\phi\phi}(0) + E . \{\phi^3(t) . K_1 x_a^3(t+\tau)\} \end{aligned} \tag{13}$$

The individual $\phi(t)$ and $x_a(t)$ signals are normally distributed. Assuming that the degree of amplification has a cubic component, the trip autocorrelation function and the product of a factor of six yields a sum, as shown in Equation (13). Measurements indicate that the additional expectation value added to the triple correlation function (Equation 13) is frequently small. The behavior of man must therefore essentially be linear. In a manner similar to that described above, in addition to the cubic degree of amplification, other nonlinearities can also be used (investigations concerning the nonlinear behavior of man have not yet been completed). Fig. 9 presents a measured result. /942

4. Measured Results of Flight Experiments with a Hover Craft /945

In the course of the experimental development of a transport aircraft which starts and lands vertically, controllability experiments were conducted on the free-flying hover craft shown in Fig. 5. Some of the results of these experiments, conducted with the aid of 11 different test pilots from Germany, Denmark, England and the USA, are reported here.

It has been mentioned in Section 4 that measurements of the component of the transfer function of the pilot, designated there by $F_p(j\omega)$, describe the dynamic behavior only partially, because they do not include the effect of the stochastic variation of parameters. For this reason, during the controllability experiments in the House of Dornier at the evaluation of flight experiments the output spectra of deviations from the desired flight position to be adhered to and the activation of control devices were measured. The output spectra of the angle position characterizes the input information, that of the activation of control devices, the output signal of the

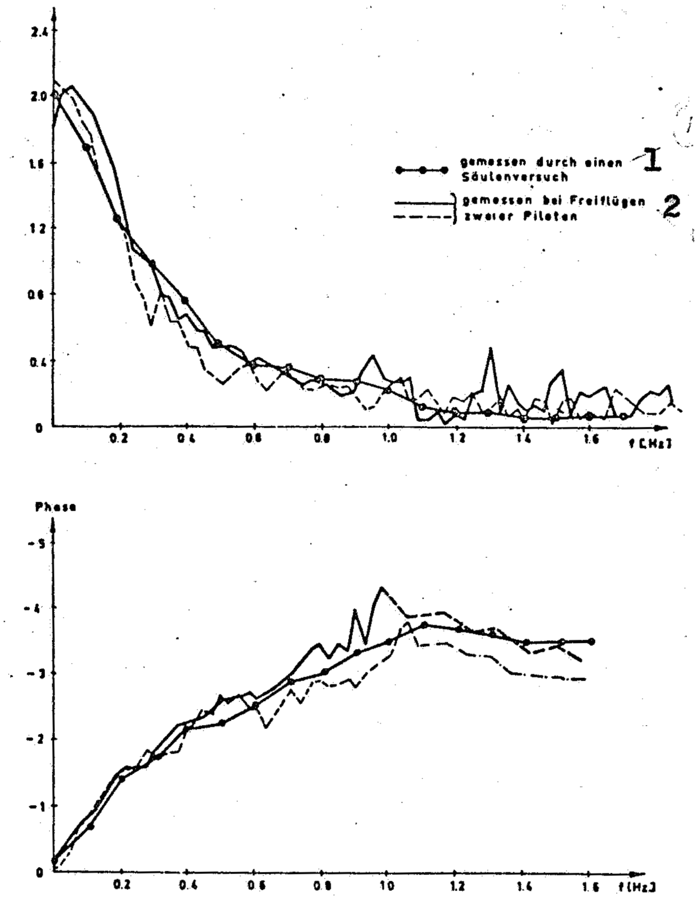


FIGURE 6. Magnitude and Phase of the Controlled Segment $F_s(j\omega)$

Keys: 1. Measured through a column experiment,
2. Measured during free flights by two test pilots

pilot. In addition to the output spectra, the constant components of the transfer functions $F_p(j\omega)$ and the pilot noise are measured.

It has been shown in /3/ that the spectrum of the noise signal $\mathcal{P}(t)$ representing the response of the system to the stochastic variation of the parameters, can be described approximately by the relationship

$$S_{pp}(f) = S_{\alpha\alpha}\bar{x}_a^2 \tag{14}$$

It has been assumed in the derivation /3/ that the stochastic parameter variations $\alpha(t)$ are of a wide-band nature. In practice, this condition is satisfied with adequate accuracy. The $S_{pp}(f)$ spectrum can always be determined in the evaluation of in-flight experiment measurements with the aid of Equation (9).

First, the influence of the training and constitution of pilots will be demonstrated by the example of a few results. For this purpose, the behavior of different pilots during the same flight problem was examined. Hover flights were performed with the experimental control stand with slow displacement over the ground. The hover craft had no artificial stabilization during these experiments.

Fig. 10a and 10b shows four different spectra of roll angles and stick operation /note/. Spectra a were measured with the chief test pilot of Bornier Company, the b spectra with a test pilot of the Hawker-Siddeley Works. Both pilots had /948 extensive flight experience in VTOL craft. The c spectra were measured with a test pilot who flew for the first time after an interruption of six months following an accident. The d spectra originated with a flight test engineer without any VTOL experience (measured during a column experiment).

It is seen in Fig. 10b that all spectra concerning the operation of the stick exhibit a characteristic resonance peak, located at a frequency of 0.4 Hz. The amplitude of the resonance peak is, however, very different. It is substantially higher with the less experienced pilots (c and d). Since the configuration of the input spectra, i.e. the deviation of the position angle from the correct angle does not show such resonance peaks, they must represent an effect of the stochastic variation of parameters (pilot noise). The latter are significantly higher in the case of inexperienced pilots.

Fig. 11 presents stick spectra of the operation of roll control during similar hover flights. All flights were performed by the same pilot. They were removed in time up to six months from each other. Fig. 11 shows that the configuration of the spectra is nearly identical.

To investigate the behavior of the pilot during flights with very strong disturbances, experiments were performed in which strong torque disturbances were imposed on the hover craft with the aid of artificial noise signals. The task of the pilot was thus made considerably more difficult. Fig. 12

presents the results of these experiments. The spectrum of the deviation from the angle position is plotted in Fig. 12b. Fig. 12a presents the corresponding spectrum of roll controls and the spectra of the imposed interferences and of the pilot noise.

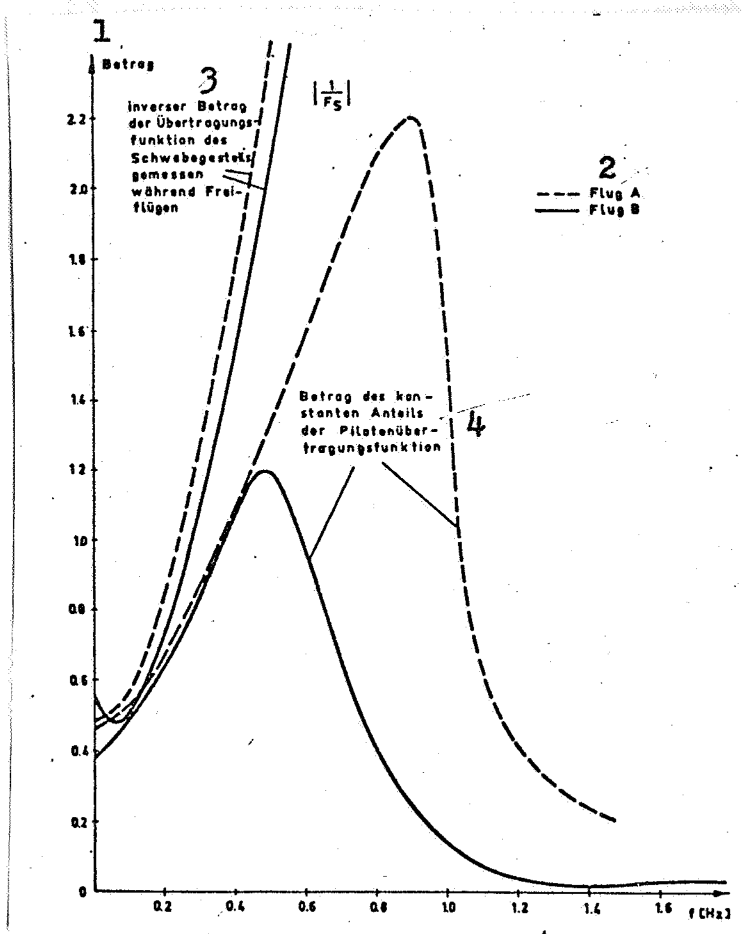


FIGURE 7. Magnitude of Two Pilot Frequency Responses and Two Inverse Sections

Keys: 1. Magnitude, 2. Flight A, Flight B, 3. Inverse magnitude of the transfer function of hover rig as measured during free flight, 4. Magnitude of the constant component of the pilot transfer function

During the testing of the experimental control rig it was seen that the relationship of the correlation of stick deflection and control momentum has a strong effect on controllability. For this reason, experiments were performed in which this ratio was systematically varied. Fig. 13 presents some of the characteristic results.

An increase in

$$\text{"stick sensitivity"} = \frac{\text{moment of inertia or control}}{\text{path of stick}}$$

in excess of a value found to be satisfactory lead according to the unanimous judgement of different pilots to a much reduced controllability. Fig. 13 represents the spectra of deviations from the angle position and stick operation for one of these experiments. In the experiment, artificial momentum disturbances were superimposed, as described above. It is seen in Fig. 13 that the pilot noise has increased substantially. This displaced the resonance frequency of the stick spectrum in the direction of higher frequencies.

Stick spectra vary strongly with the problem. Fig. 14 shows some spectra for the roll control of the experimental /950 control rig with various control devices. Spectrum a was determined during an experiment with angle position control, spectra b and c during flights with angle velocity control or damping control and spectrum d during a flight with manual control without artificial stabilization. Spectra a to c have substantially narrower bands as compared with d, because due to the ease of the problems pilot noise is significantly less.

In addition to the performance spectra and pilot noise, the constant components of the transfer function of man were also measured. Fig. 15 shows some of the results. The frequency responses of the pilot exhibited the obvious property that the action time and degree of amplification increase with the degree of difficulty felt by the pilot. The configuration /951 of a shows the result of a normal flight without artificial stabilization, the configuration of b the result of a flight with manual control and strong momentum interferences; the configuration of c presents the frequency response of the manually controlled flight with strong disturbances and unfavorable stick sensitivity.

The measured results described in Section 4 may be summarized as follows:

The level of pilot performance and the constitution of the pilot can be measured by the method described. Different levels of training of the same pilot are recognizable as are different degrees of experience in the case of increased phase lags and rising degrees of amplification by the pilots. The /954 performance component of the noise signal produced by the pilot rises with increasing degrees of difficulty of the problem and declines with growing experience. With the same aircraft and pilot, variations in the handling of operating defices are observable in the performance spectra.

5. Measured results of Controllability Investigations on Helicopters with a Simulator

In the course of a research contract involving the controllability of helicopters, simulation experiments were performed in the House of Dornier. The helicopter was represented by a model of a system with six degrees of freedom. The degree of freedom of shock motion was taken into consideration in the determination of the flight-mechanical data. It is assumed that the number of revolutions of the rotor is kept constant by a regulator. Since only hover flights and slow forward flights were to be considered, it was possible to linearize the equations of motion.

The simulation of flight-mechanical characteristics is readily accomplished with the available hybrid computer. The same is true for the corresponding calculations of the cockpit and the operating controls. Difficult problems are caused, however, by the simulation of information for sensory perception, e.g. of visual and acceleration information. The simulation of acceleration information in the Dornier simulator was purposedly neglected. Visual information was simulated with the aid of the model shown in Fig. 16 on a sheet. The information is represented in perspective corresponding to the angle position of the aircraft. Translation motions are recognized by the divergent lines.

Some of the results of the simulation experiments are described in the following. Fig. 17 shows e.g. the spectra for the operation of the stick and the pedals during a hover flight with a Sikorsky S-58 helicopter with and without significant external disturbances.

It is seen in Fig. 17 that the spectra for the operation of the roll and pitch controls have narrow bands and are without resonance peaks. Controllability was declared very good. Due to the favorable control characteristics, pilot noise was very low. This lead to low-frequency spectra. The very strong applied moment interferences did not change the results fundamentally. Since the spectra of the disturbances exhibited rather wide bands, the spectra for the roll and pitch controls necessarily became somewhat wider also. However, no resonance peaks are formed. The spectra for yaw controls always have somewhat broader bands and exhibit clear resonance peaks. The spectrum for the yaw control became somewhat wider during the /955 disturbed simulated flight, although only roll and pitch moment interferences were applied. The reason for this is to be found in the unavoidable interaction between motions around the individual axes. The resonance peak of the spectra for the yaw control is presumably caused by the nature of the simulated visual information. It is seen in Fig. 16 that the point of convergence of the lines converging toward the horizon moves during yaw motions. Since this point can leave the image rather rapidly while the pilot is trying to prevent this from happening, he feels that the task is more difficult than it is in reality. During free flights the pilot does not have the feeling that the point of aligmment might disappear during turns.

Fig. 18 presents the corresponding spectra of two simulated experiments of a jet helicopter of the Do 32 series. The jet helicopters of the Do 32 family, designed and partially built by Dornier, are characterized by very good control properties. During undisturbed hover flights only small, low-frequency /959 movements are required to control the craft, principally because the noise signals introduced by the pilot himself are practically equal to zero. Since in the case of these jet helicopters the yaw motion is largely isolated, its control is felt to be easy. This results in a vary narrow-band spectrum. In disturbed flights with large momentum interferences in the roll and pitch motions the shape of the spectra does not vary greatly. As /960 the result of the interferences to be controlled, however, their band becomes somewhat broader.

To compare the control experiments of the jet helicopter with the results of simulation experiments performed with a mechanical helicopter of the same class. Such data is presented in the following. Fig. 19 presents some results of strongly disturbed hover flights. Here, momentum interference was simulated both in the roll and pitch motion. It is seen from the configuration that the pilot noise does increase. The pilot is thus exposed by very disagreeable control characteristics. Interference signals introduced by the pilot himself lead to very wide spectra in the control process around all of the axes.

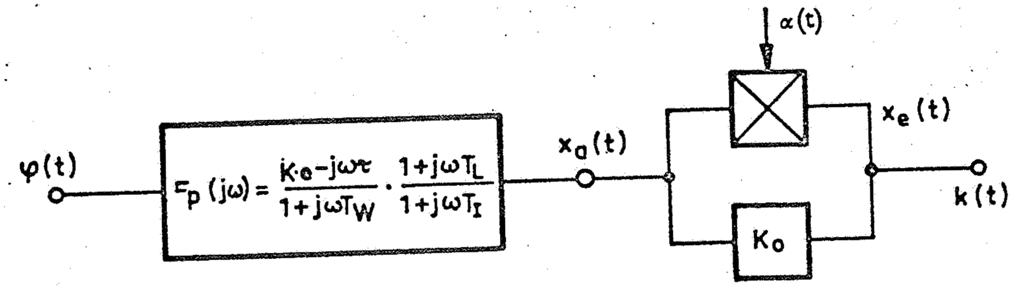


FIGURE 8a. Model of Man as Controller with Multiplicative Noise

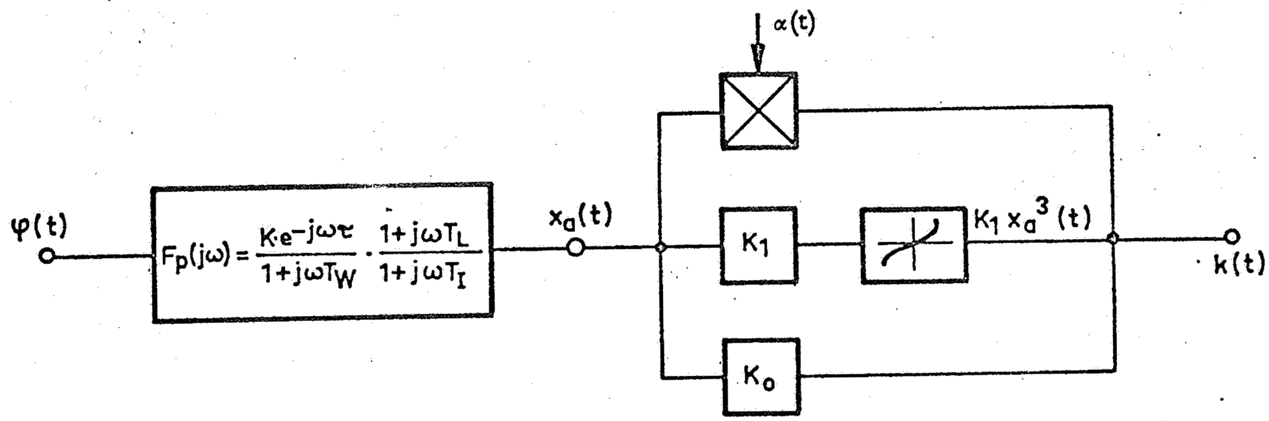


FIGURE 8b. Model of Man as Controller with Multiplicative Noise and Nonlinear Amplification

/943

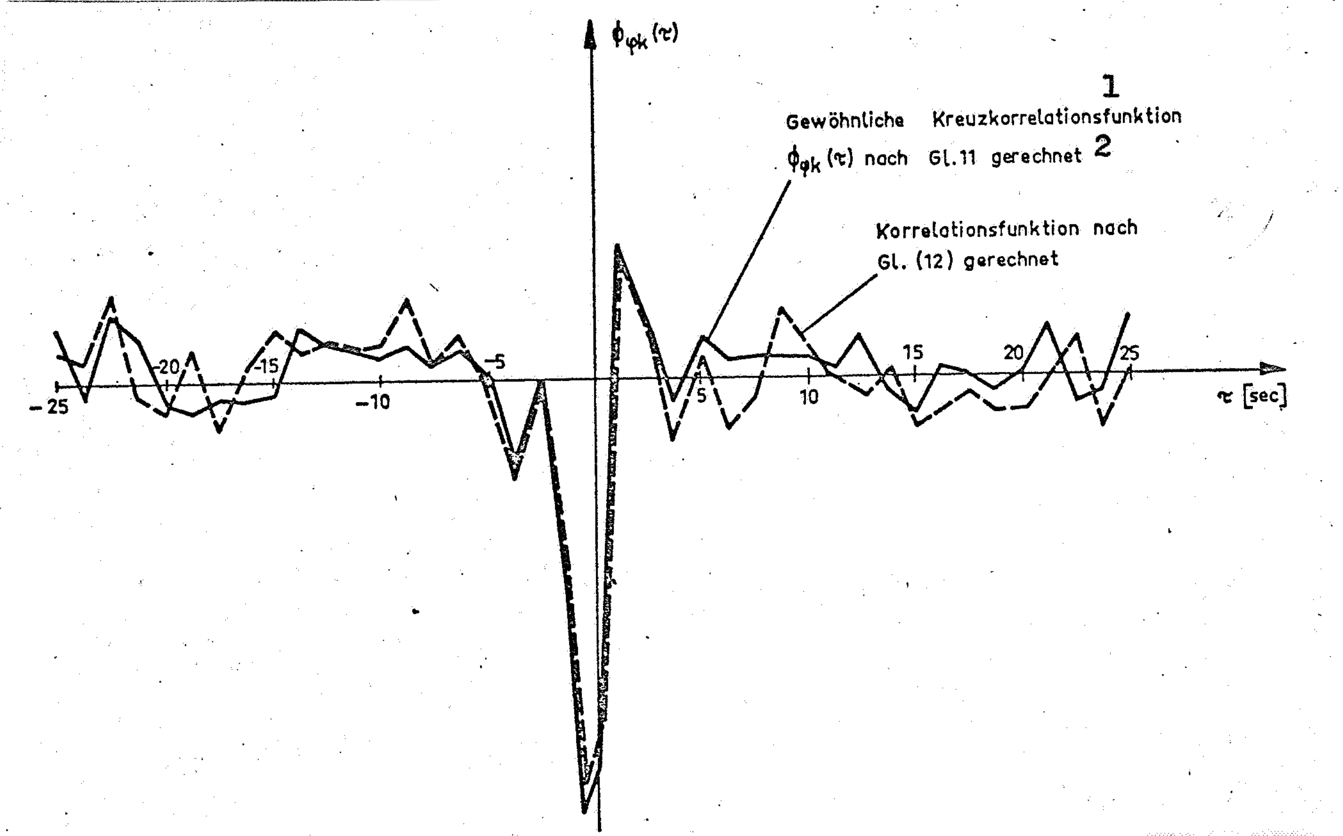


FIGURE 9. Crossover Correlation function Between Roll Angle and Stick Operation in a Free-Flight Experiment with the Hover Rig.

Key: 1. Ordinary crossover correlation function calculated according to Equation (11).
2. Correlation function calculated according to Equation (12).

/944

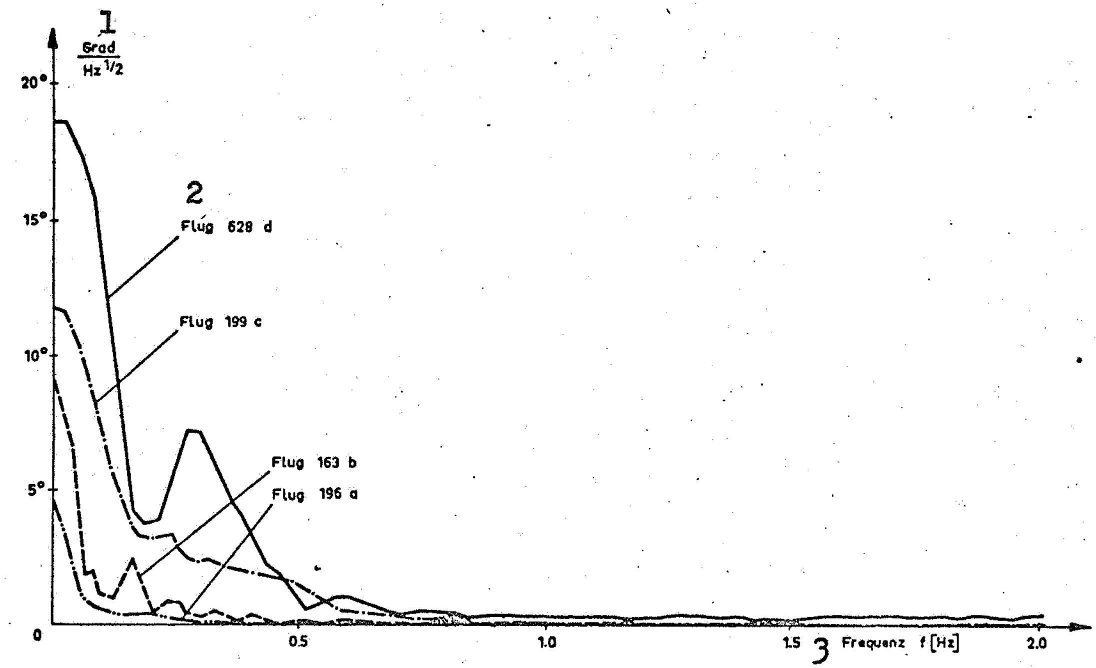


FIGURE 10 a. Spectra of the Deviation of Rolling During Flights by Four Different Pilots

Keys: 1. Degree, 2. Flight, 3. Frequency

/946

/947

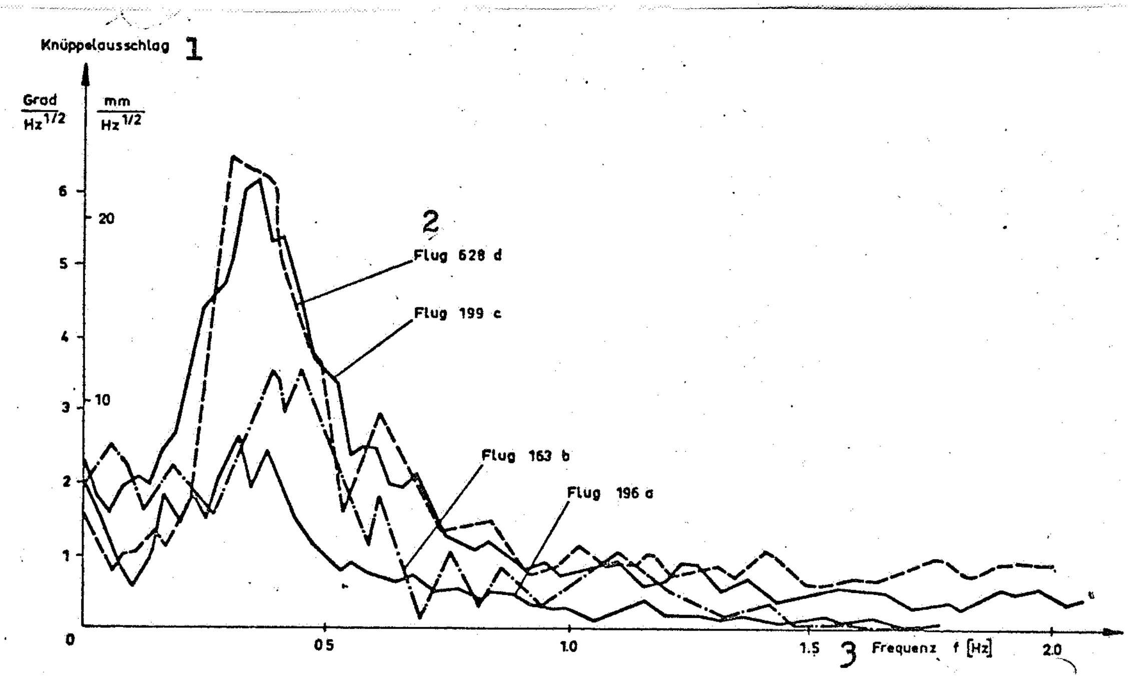


FIGURE 10b. Spectra of the Stick in Controlling Roll Motion with Four Different Pilots

Keys: 1. Stick deviation, 2. Flight, 3. Frequency

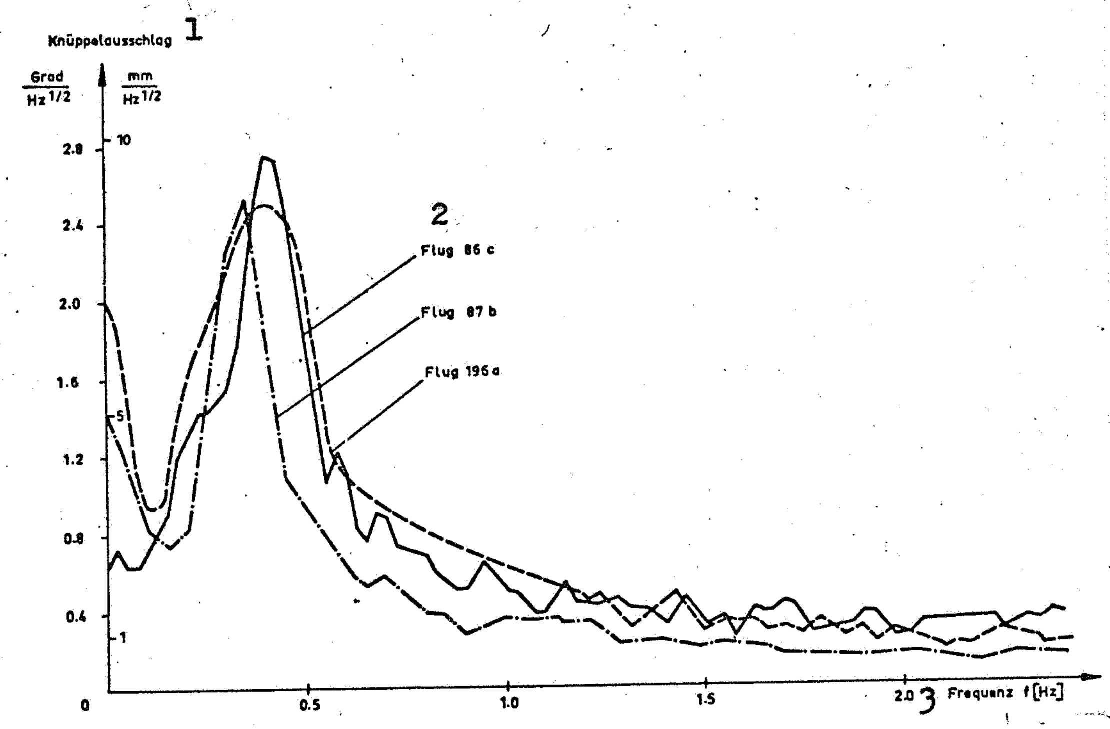


FIGURE 11. Stick Spectra in Controlling Roll Motion

Keys: 1. Stock deviation, 2. Flight, 3. Frequency

/949

/950

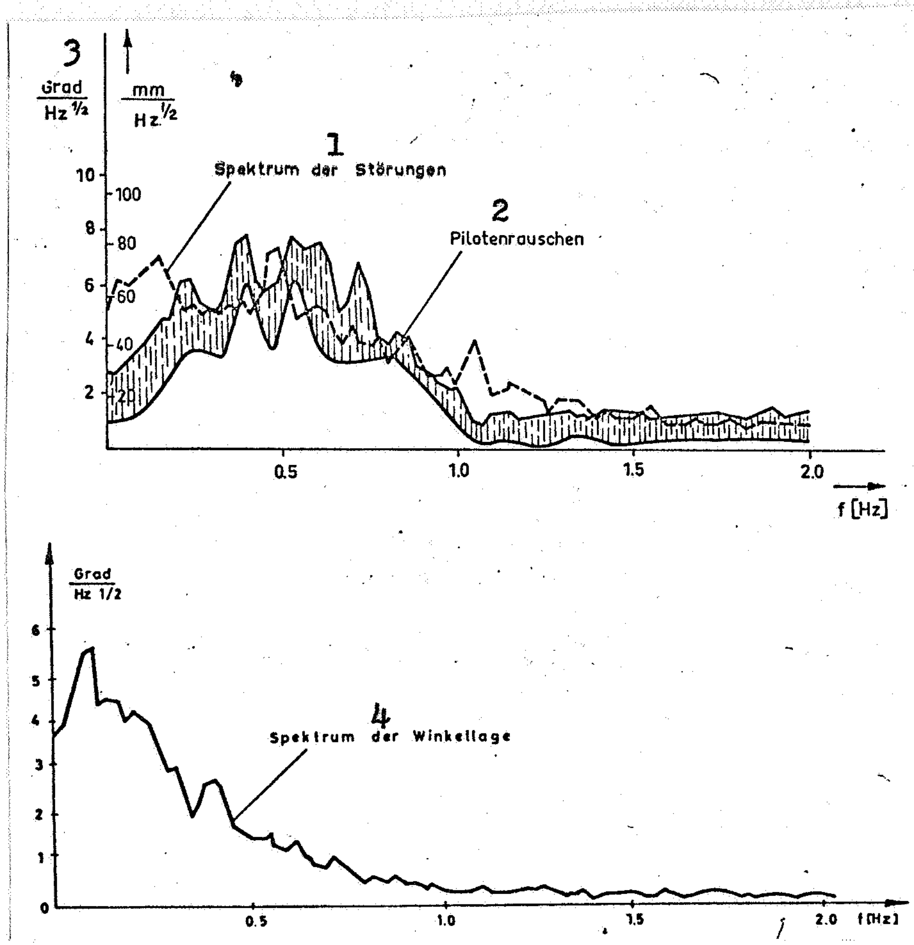


FIGURE 12. Spectra of Roll Control and Roll Motion with Strong Interference

Keys: 1. Spectra of interferences, 2. Pilot Noise, 3. Degree, 4. Spectrum of angle position

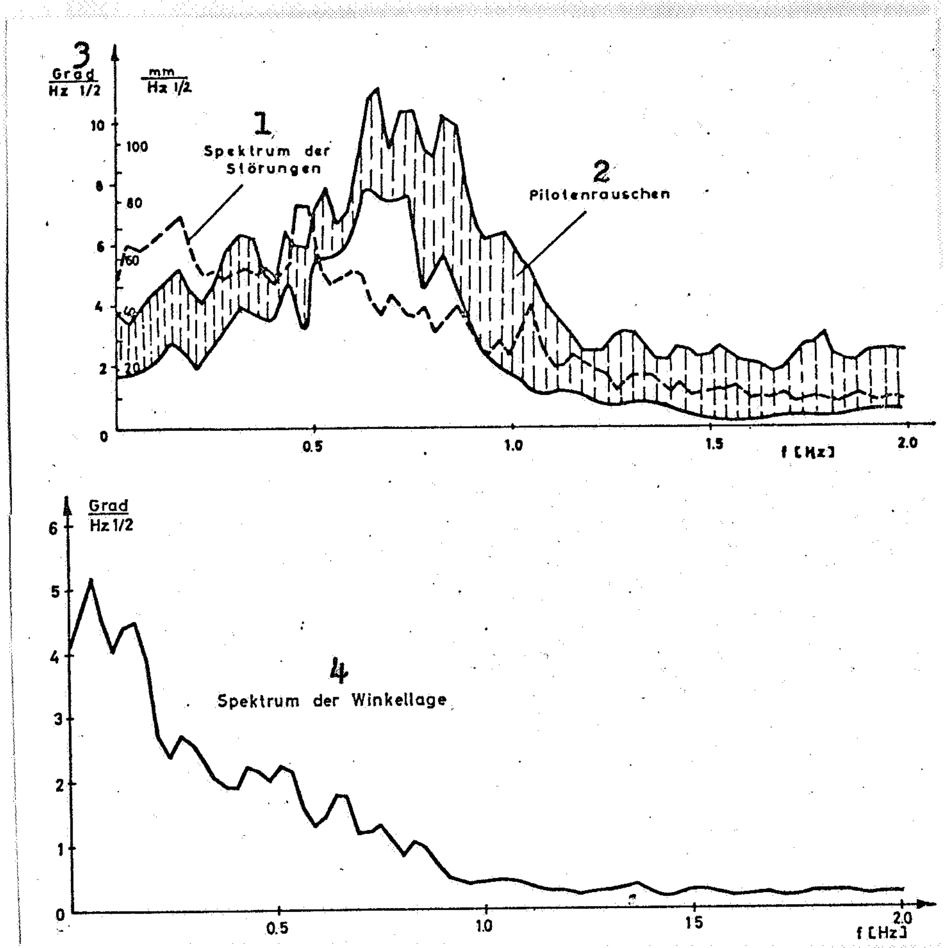


FIGURE 13. Spectra of Roll Control and Rollage with Strong Interference and Unfavorable Stick Sensitivity

Keys: 1. Interference spectrum, 2. Pilot noise, 3. Degree, 4. Spectrum of angle position

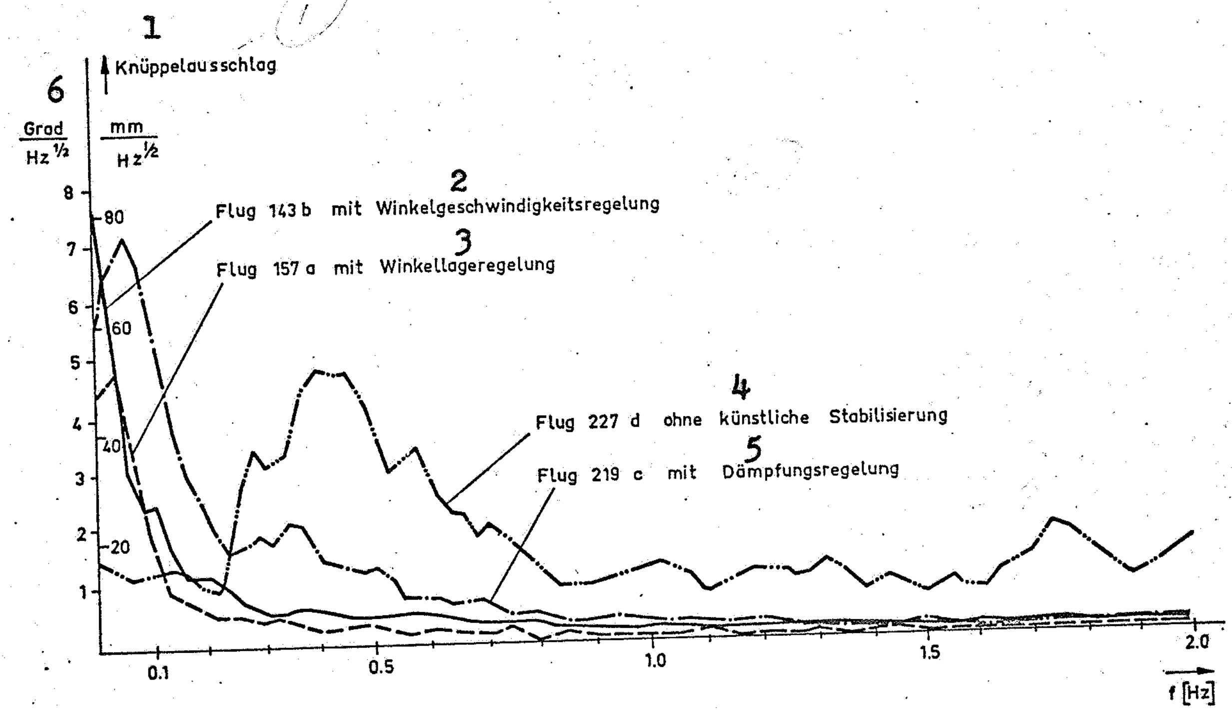


FIGURE 14. Performance Spectrum of Stick Deflection With Various Controls

Keys: 1. Stick deflection, 2. Flight 143b with angle velocity control, 3. Flight 157a with angle posiion control, 4. Flight 227d without artificial stabilization, 5. Flight 219c with damping control, 6. Degree

/952

/953

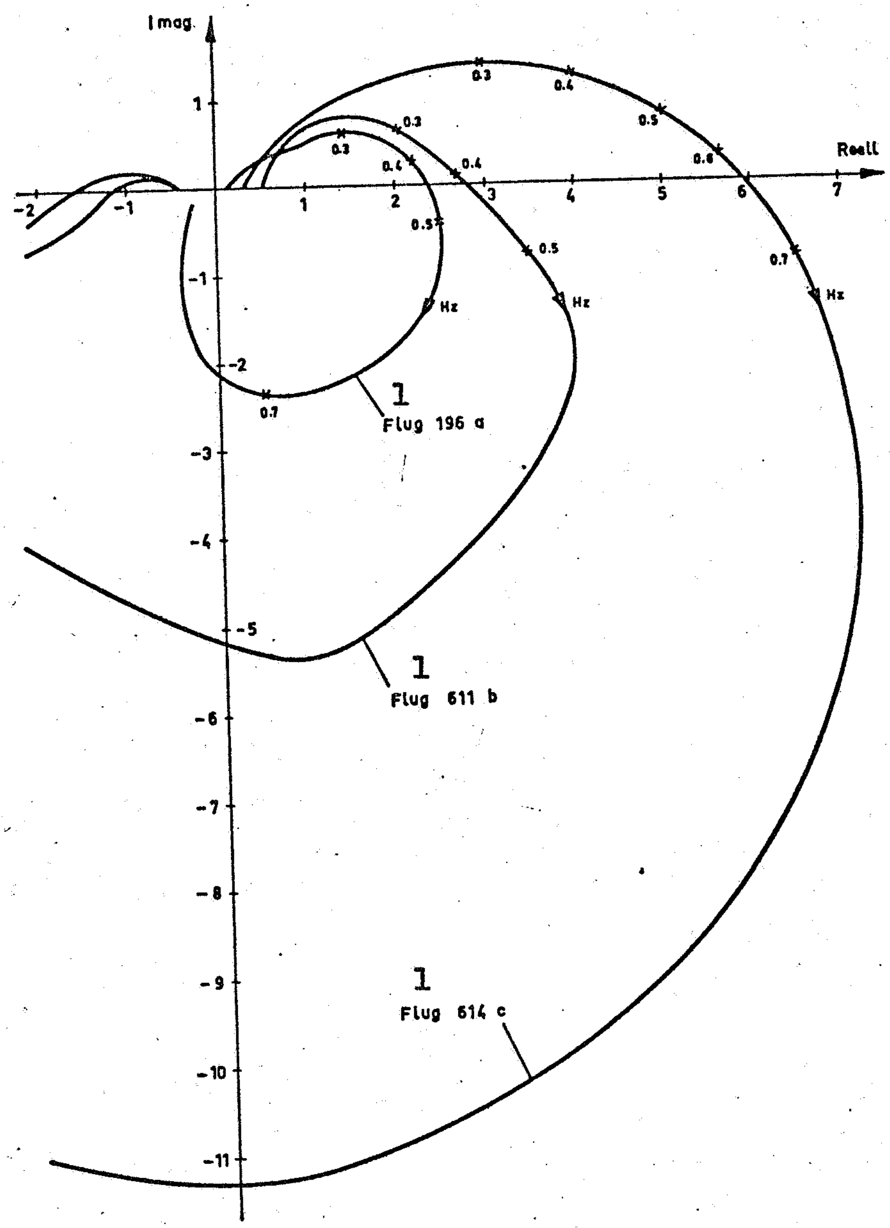


FIGURE 15. Pilot Frequency Response During Different Flights

Keys: 1. Flight

/955

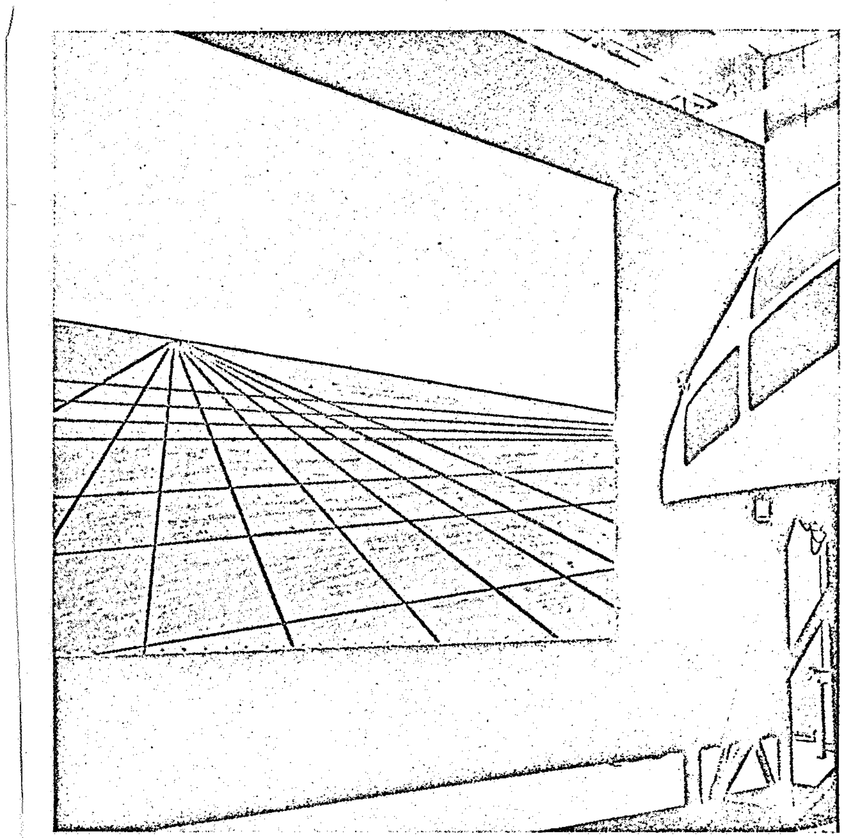


FIGURE 16. Sight Simulation of the Dornier Flight Simulator

6. Conclusions

/960

Advanced theories of control technology and the data-processing facilities which become available recently, together with digital computers make it possible to perform objective analytical investigations and flight and simulation measurements. The conditions of the experiments described above -- quasistationary behavior and Gaussian processes -- were essentially satisfied.

Results obtained with the aid of modern data processing permit a much better insight in the processes occurring during the control of aircraft than the methods applied heretofore. The purpose of subsequent investigations will be to attempt to establish with the use of advanced methods, new control criteria to optimum simplicity.

/956

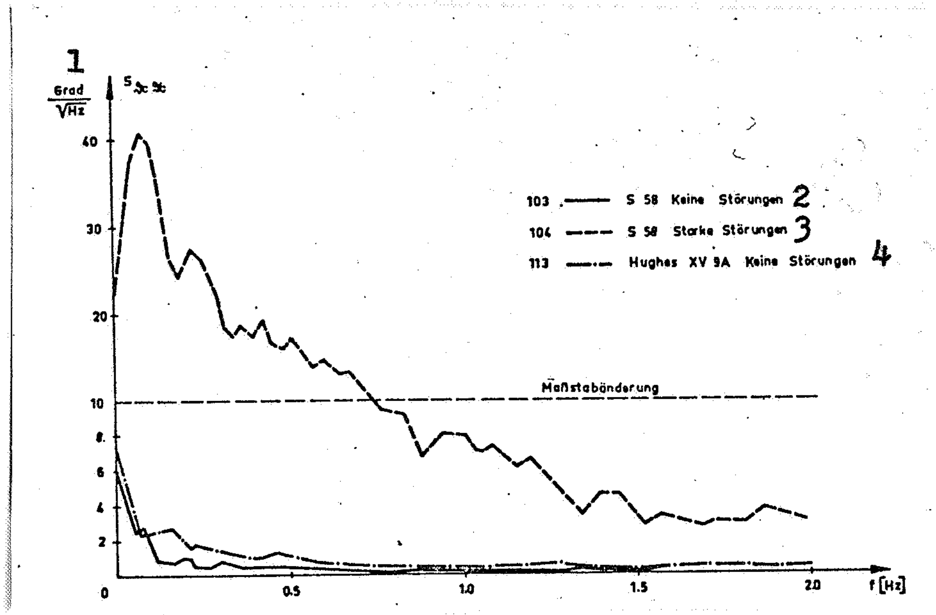


FIGURE 17a. Spectra of Stick Handling in Roll Control

Keys: 1. Degree, 2. Small interference, 3. Large interference, 4. No interference

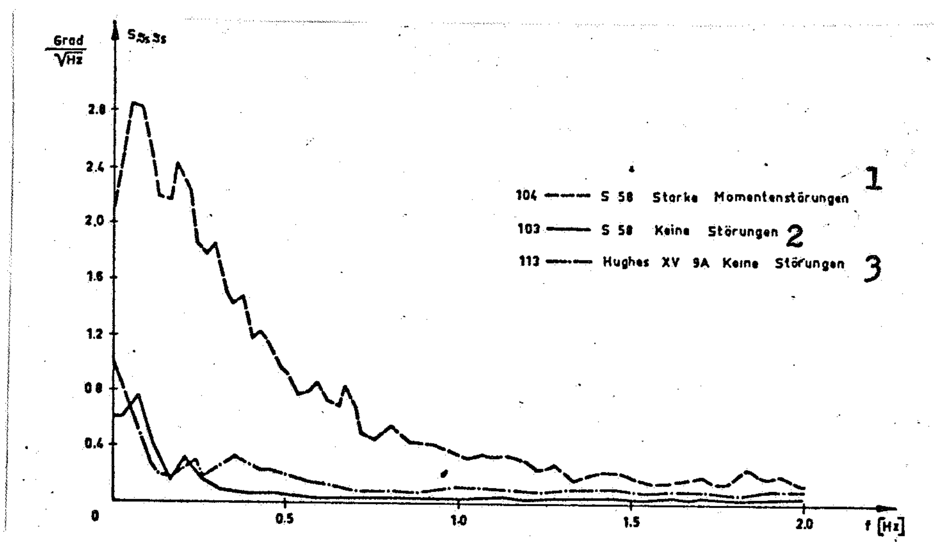


FIGURE 17b. Spectra of Stick Handling in Pitch Control

Keys: 1. Strong momentum interference, 2. Small interference, 3. No interference

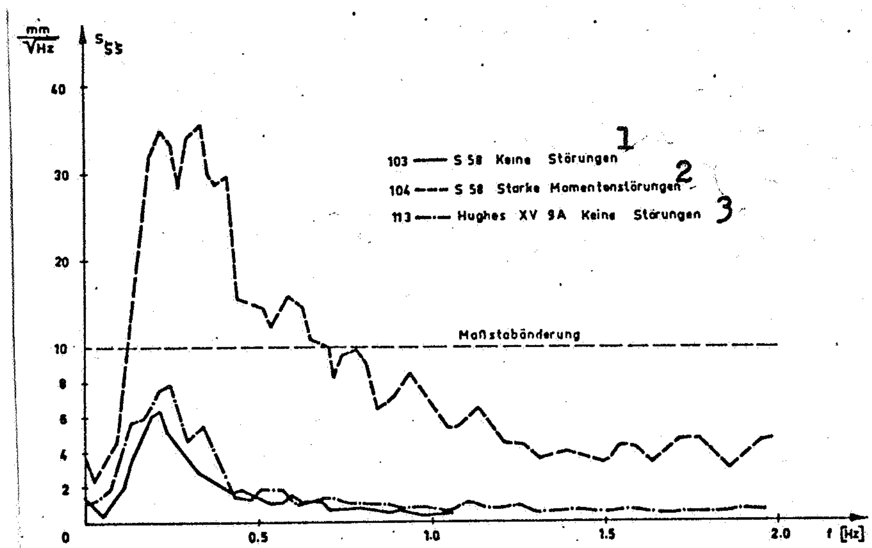


FIGURE 17c. Spectra of Pedal Activation During Yaw Control
Keys: 1. No interference, 2. Strong momentum interference, 3. Large momentum interference

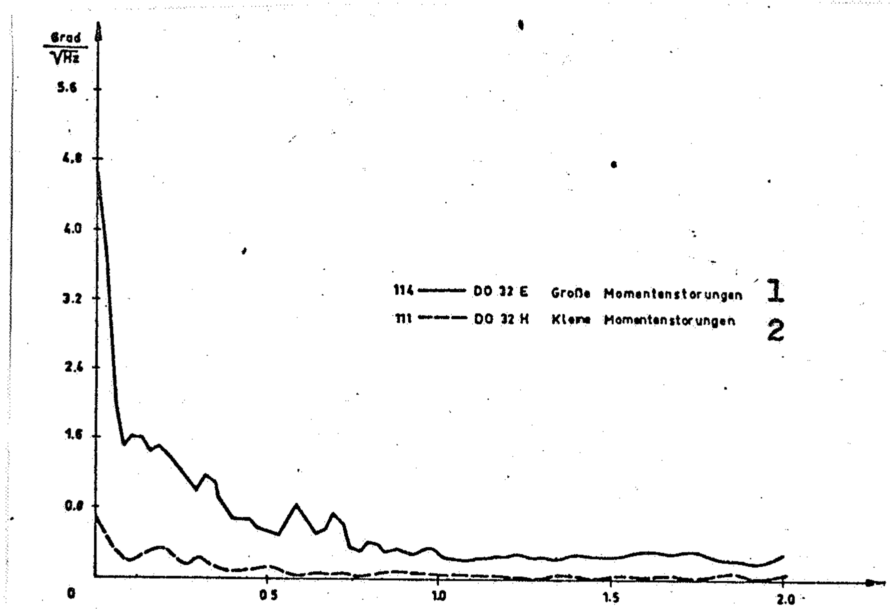


FIGURE 18a. Spectra of Stick Handling in Roll Control
Keys: 1. Large momentum interference, 2. Small momentum interference

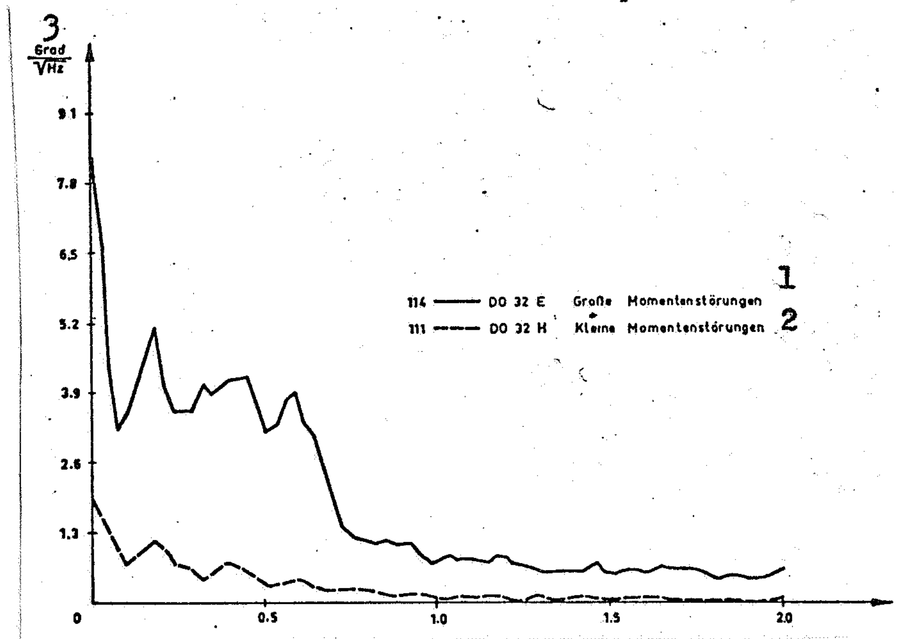


FIGURE 18b. Spectra of Stick Handling for Pitch Control
Keys: 1. Large momentum interference, 2. Small momentum interference, 3. Degree

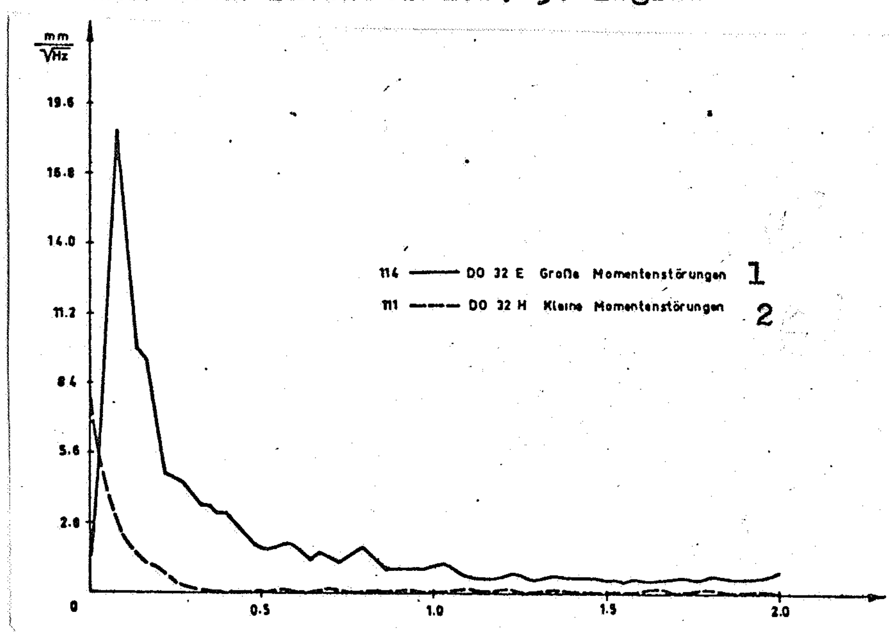


FIGURE 18c. Spectra of Pedal Activation for Yaw Control
Keys: 1. Large momentum interference, 2. Small momentum interference

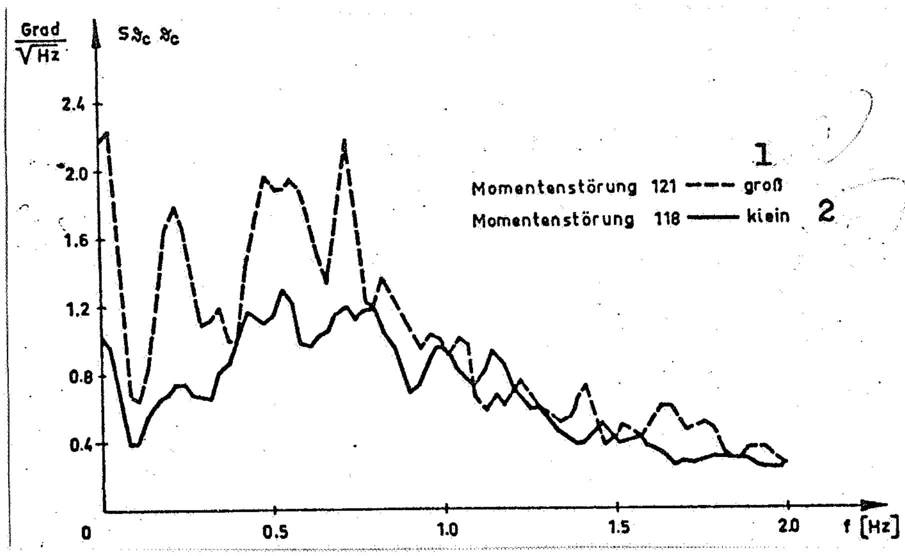


FIGURE 19a. Spectra of Stick Handling for Roll Control
Keys: 1. Momentum interference 121 - large,
2. Momentum interference 118 - small

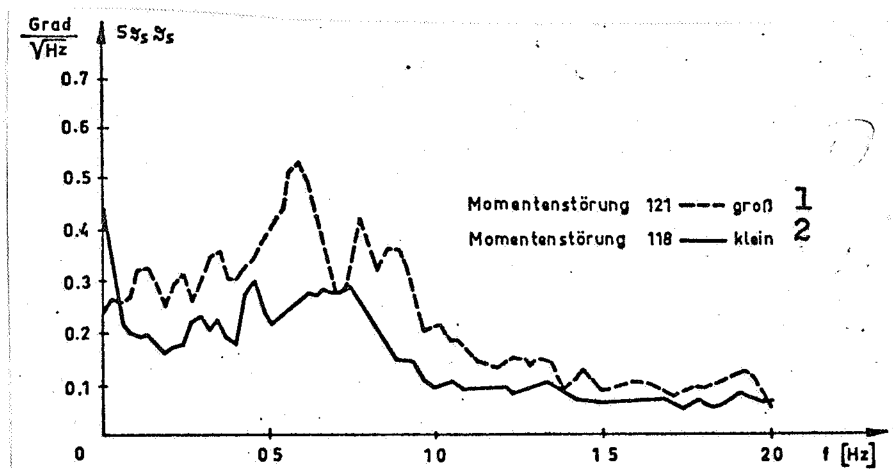


FIGURE 19b. Spectra of Stick Handling for Pitch Control
Keys: 1. Momentum interference 121 - large,
2. Momentum interference 118 - small

REFERENCES

/961

/1/ McRuer, D. T., Krendel, E. S.: "Dynamic Response of Human Operators", WADC TR 56-524, Wright Patterson AFB, Ohio, 1957

/2/ Tustin, A.: "An Investigation of the Operator's Response in Manual Control of a Power-Driven Gun", C. S. Memorandum No. 169, Metropolitan-Vickers Electrical Co., Ltd. Sheffield, England, 1944.

/3/ Schweizer, G.: "Pilot Behavior in VTOL Airctaft", AGARD Report No. 521.

/4/ Schweizer, G., Kreil, W.: "Man as Controller", (to be published in "Regelungstechnik" (Control Technology), Dornier Report No. 5614-Fo5.

DISCUSSION

Henry R. Jex (Systems Technology, Inc. 13766 South Hawthrone Boulevard, Hawthorne, California): /in English/ This paper presents excellent in-flight research which has been sadly lacking up to now. Extensive laboratory describing functions measurements at STI /see note/ show similar control spectra, and, qualitatively at least, support these results. It would be interesting to know if the present results, when plotted as total open-loop describing functions on a Bode plot, (log $|Y|$ against logω) confirm the in-flight validity of the "crossover" model, or its extended form, of the reference, e.g.:

$$Y_{OL}(j\omega) = Y_p \cdot Y_c \doteq \frac{\omega_c}{j\omega} \exp\left[-j(\tau_e\omega + \alpha/\omega)\right]; \quad \text{near } \omega_c$$

If the data do fit this model, then the large peak seen in the control power spectral densities are probably due to small stability margins and are a clue to the crossover frequency and gain. Then, under difficult wide-band input conditions, the pilot may, as shown in the reference, use a low-grain technique ("ω-regression") to suppress the peak. This would suggest caution in relating poor handling qualities to a peak in the control spectra.

/Note/: McRuer, Graham, Krendel, Reisener, "Human Pilot Dynamics in Compensatory Systems - Theory, Models and Experiments with Controlled Element and Forcing Function Variations", USAF AFFDL-TR-65-15, January 1966.

Also, there is some question on the validity of F_p obtained without any command or disturbance inputs, since under such circumstances $F_p \doteq 1/F_s$ should be obtained.

Would the authors please comment?

G. Schweizer /in German/: The author of the discussion note /962 has doubts whether with the method used in the work the transfer function of the part with constant parameters -- i.e. the F_p of the pilot is in fact obtained. It should be noted in this connection that this result will be obtained if the variation in the parameters of the pilot model is mainly multiplicative in nature. In our measurements -- both in free flight and at the simulator -- this was true. It would be highly interesting, however, to have the experiments outlined in the report, which provide information concerning the nature of pilot noise, repeated independently at another location in order to obtain still more information.

The author also suggests to verify whether the results obtained in his reference can be reconciled with the results of the experiments of the preceding report. Such experiments are now in progress. Results are reported subsequently. Our experience indicates that resonance peaks are observed in the performance peaks at high frequencies with man-machine systems, in cases when the pilot is barely able to perform his function. Presumably, one can then speak of a stability limit. From our viewpoint there are no contradictions between the work on which the foregoing discussion note is based and our own results.

/960

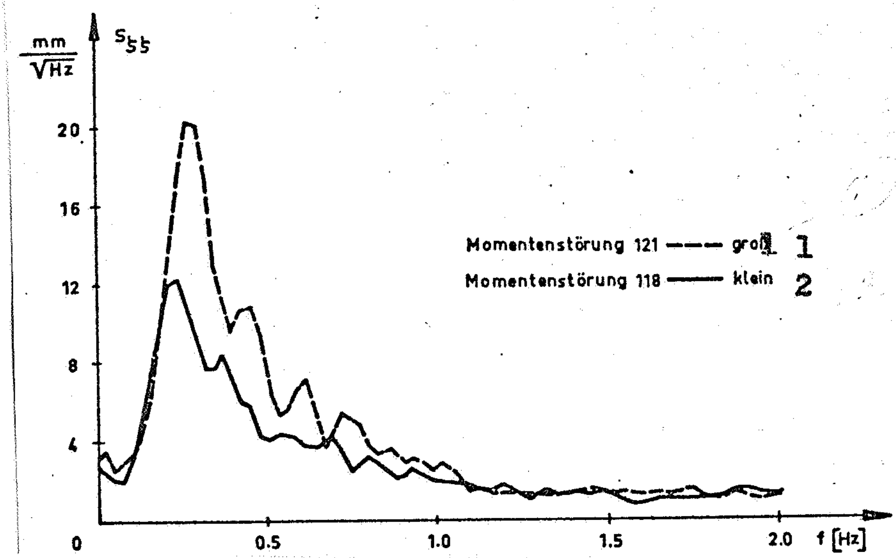


FIGURE 19c. Spectra of Pedal Activation in Yaw Control

Keys: 1. Moment interference 121 - large,
2. Moment interference 118 - small.